Mechanism and Machine Theory 92 (2015) 17–28

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Dynamic analysis and experimental study of a marine gearbox with crossed beveloid gears

Song Chaosheng *, Zhu Caichao, Liu Huaiju, Ni Gaoxiang

The State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400030, China

ARTICLE INFO

Article history:
Received 23 October 2014
Received in revised form 3 May 2015
Accepted 4 May 2015
Available online xxxx

Keywords:
Marine gearbox
Beveloid gears
Crossed axes with small shaft angle
Coupled dynamics
Experimental study

ABSTRACT

Dynamic modeling of beveloid gears is less developed than that of conventional involute gears with parallel axis because of their complicated mesh mechanism and 3-dimensional dynamic coupling. For evaluating the dynamic characteristics of a marine gearbox with crossed beveloid gears more realistically, a systematic dynamic modeling approach was proposed based on the lumped parameter and the finite element method. Considering the time-varying mesh stiffness excitation, time-varying loaded translational transmission error excitation, sliding friction excitation and backlash nonlinearity, a coupled gear–shaft–bearing–housing dynamic model for a marine gearbox with crossed beveloid gears was developed based on the proposed modeling method. Then, numerical integrations applying the explicit Runge–Kutta formula and the implicit direct integration were used to solve the nonlinear dynamic model. The dynamic transmission error, dynamic mesh force, and dynamic equivalent shaft-bearing supporting force were obtained as well as the dynamic response of the housing. Finally, a test rig was established for the marine gearbox with crossed beveloid gears and vibration tests were performed to investigate the dynamic responses. Through analyzing the responses in time domain and frequency domain, the experimental results compared well with the theoretical dynamic results.

1. Introduction

Beveloid gears are used in high-speed marine gearboxes with small shaft angle to meet the requirements of ahead and reverse running for yachts. The application of crossed and intersected beveloid gears in marine transmission is shown in Fig. 1. This type of marine gearbox can lower the mounting height of the engine room and provide a necessary water-entry angle for the propeller to decrease the draught and running resistance for yachts and fast ferries. The transmission schematic for the marine gearbox is shown in Fig. 2. However, with the increased requirements for high speed, efficiency, reliability and good load capacity, vibration and noise have become the key influences on the transmission performance of this type of gearboxes.

In recent years, numerous studies have been conducted on the geometry design, manufacturing, static contact characteristics and geared rotor dynamics for beveloid gearing. For beveloid gearing design, Brauer [1] derived the mathematical model of a straight beveloid gear tooth surface and calculated the minimum value of the inner transverse addendum modification coefficient to avoid undercutting. Liu [2] investigated a generating method for the internal beveloid gear with a shaping machine by inclining the shaper-arbor with respect to the gear axis. Mitome et al. [3] proposed a design method for a type of nonintersecting–nonparallel-axes beveloid gears having line contact tooth surfaces. Wu and Tsai [4] proposed a geometry design for crossed beveloid gear drives in approximate line contact. Zhu et al. [5] proposed a pitch coned geometry design method for the crossed beveloid gear used in marine transmission. The inclining work-arbor taper hobbing and the table sliding taper hobbing methods, which are the most

* Corresponding author. Tel.: +86 13883402720.
E-mail address: chaoshengsong@hotmail.com (C. Song).

http://dx.doi.org/10.1016/j.mechmachtheory.2015.05.001
0094-114X/

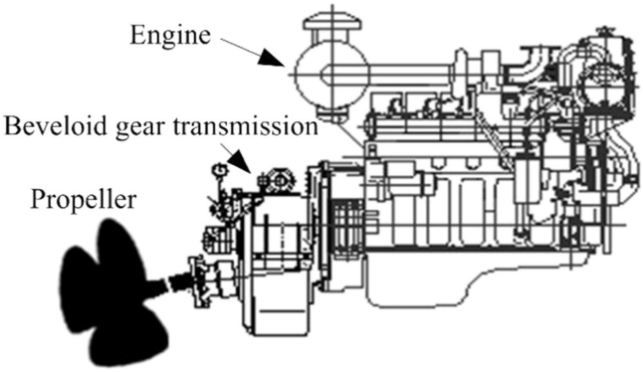

Fig. 1. Layout of marine gearbox.

popular ways for manufacturing this type of gearing, were first proposed by Mitome [6,7]. To finish straight beveloid gears, Mitome [8] developed three grinding methods which are Niles-type infeed grinding, table sliding infeed grinding and inclining work-arbor infeed grinding. Brecher et al. [9] investigated the influence of the machine kinematics and the tool concept on the running behavior of beveloid gears. For the contact behaviors of beveloid gears, Liu and Tsay [10], Ohmachi et al. [11], Wu and Tsai [12], Brecher et al. [13], and Song et al. [14,15] investigated the effects of design parameters on tooth contact behaviors which included the contact pattern, root stress, transmission error and mesh stiffness for beveloid gears. In the aspect of dynamic, Song et al. [16–18] proposed 14 degrees of freedom dynamic model for crossed beveloid geared rotor system using the lumped parameter method. The effects of geometry design parameters, load and misalignments on the dynamic transmission error, dynamic mesh force and effective dynamic bearing force were investigated in those work. However, the studies mentioned above are mainly focused on the geometry design, manufacturing and tooth contact analysis to enhance the surface durability. Previous studies on beveloid gear dynamics are very limited and only focus on the geared rotor system. Few studies discussed the systematic dynamics of the beveloid gearbox considering time-varying beveloid gear mesh characteristics, shaft–bearing connection and housing.

In this paper, a systematic dynamic modeling approach was proposed and a coupled gear–shaft–bearing–housing dynamic model for marine gearbox with crossed beveloid gears was created. Then, numerical integrations applying the explicit Runge–Kutta formula and the implicit direct integration were used to solve the nonlinear dynamic model and the dynamic characteristics of the marine gear system were investigated. Finally, vibration tests for the marine gearbox were performed to verify the simulation. This work is believed to help people to gain a better understanding of the systematic dynamic modeling and the dynamics of this type of gears.

2. Systematic coupled dynamic modeling

Due to the complicated tooth surface geometry and consequently time-varying and spatial-varying mesh behaviors, the actual excitations and the dynamics of marine gearbox with crossed beveloid gears are very complex. To develop the systematic dynamic model, the marine gearbox was divided into two sub-systems: the geared rotor sub-system and the housing sub-system. First, a multi-body lumped parameter dynamic model [18] with 14 degrees of freedom was used to describe the beveloid geared rotor sub-system as shown in Fig. 3. Then, the equivalent dynamic bearing forces calculated from the geared rotor sub-system were imported to the housing dynamic sub-model which was developed by finite element method. Finally, the structural dynamic response

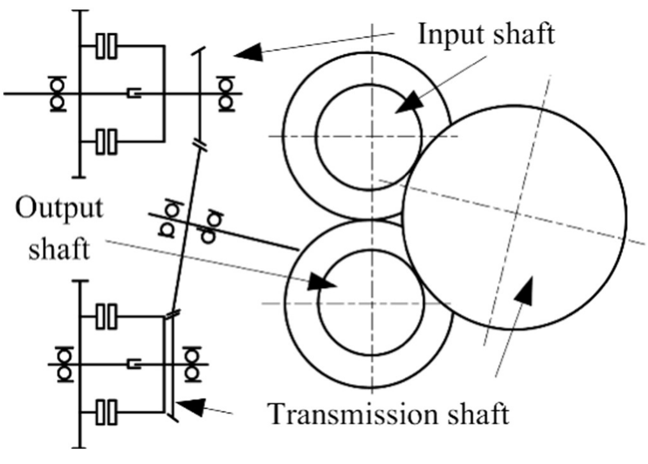

Fig. 2. Transmission schematic of marine gearbox.